A Compact Depth-fused 3-D Display Using a Stack of Two LCDs

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Abstract

We have developed a compact three-dimensional (3-D) display using a depth-fused 3-D (DFD) visual illusion in which two overlapped images with edges displayed at different depths can be perceived as a 3-D image. To make the display compact, we utilize the apparent luminance summation using the summation of polarization-angle changes at two transparent liquid-crystal displays instead of direct luminance summation. This enables moving color 3-D images to be shown on a compact display. Our compact DFD display is promising for various applications, such as cellular phones, personal digital assistants, and computer monitors.

1. Introduction

Three-dimensional (3-D) display technology can present the real world at which we are usually looking and show a high degree of realism. Current 3-D display mechanisms [1] are stereoscopy, integral photography, the differential binocular vision method [2], volumetric display [3], and holography [4]. However, at this stage, the only practical 3-D display for electronic color moving 3-D images is the stereoscopic display, which needs special equipment, such as a lenticular sheet or a parallax barrier in front of the display or glasses for observers.

Volumetric display technology, which currently uses many display planes, is being researched with the aim of developing a method of showing 3-D images with a small number of planes. When an observer perceives two transparent images with different depths, the depths of the front and rear images can usually be distinguished using binocular disparity. Ando [2] discussed the depth perception of two transparent images with particular patterns using the differential binocular vision method. He deduced that their retinal images are almost the same as those of a single image at an intermediate depth between the two transparent images only when the two overlapped images have particular luminance distributions that are differentiable and change very slowly and have very little depth difference. However, the depth perception of two overlapped images with many edges, whose retinal images are significantly different from those of a single image at intermediate depth, was not reported until our recent reports [5]-[7].

We proposed that two transparent images with many edges can be perceived as continuous 3-D images, called the depth-fused 3-D (DFD) visual illusion [8]. We also developed a DFD display using it, which needs only two conventional 2-D displays and a half mirror without any extra equipment for observers. It enables an observer to perceive apparent 3-D images with many edges between the two 2-D displays when their luminances are divided between them according to the 3-D image depth.

In this paper, we report a new DFD display that utilizes the summation of polarization rotation angles among two transparent liquid-crystal displays (LCDs) instead of the direct luminance summation [9]. This enables a very compact 3-D display using the DFD visual illusion. This 3-D display can be applied to various devices, such as cellular phones, personal digital assistants (PDAs), and computer monitors. We have developed a prototype of the com-

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pact DFD display using the DFD visual illusion and confirmed that color moving 3-D images can be displayed.

2. DFD visual illusion and previous 3-D display

The DFD visual illusion is perceived when two images with many edges in the front and rear frontal-parallel planes at different depths are overlapped from the viewpoint of an observer, as shown in **Fig. 1(a)**. The alignment and magnification of the front and rear images are arranged such that the images are viewed as completely overlapped at the midpoint between the observer's eyes. The images are created from an original 2-D image projected from a 3-D space. The only difference between them is their luminance distributions, which are calculated according to the depth of each object in 3-D space. When the luminance ratio between the two images at each point is obtained from the distance ratio between the object and the two image planes, observers perceive an apparent 3-D image (i.e., a depth-fused image) that has a continuous range of depth between the front and rear planes as illustrated in Fig. 1(c). Specifically, when the front-image luminance ratio is higher than the rear-image luminance (e.g., the stuffed animal in Fig. 1), the depth-fused image is perceived to be near the front plane. When the front-image luminance ratio is lower than the rear-image luminance (e.g., the house), the depth-fused image is perceived to be near the rear plane. When the front and rear-image luminances are almost the same (e.g., the doll), the depth-fused image is perceived to be intermediate between the front and rear planes. A gradual change in luminance ratio in the vertical and horizontal directions (e.g., the floor and side curtain) is perceived as a 3-D image occupying a continuous range of depth.

In our recent reports [5],[6], the front and rear images were optically formed using a half mirror, as shown in **Fig. 2**. This easily added the luminances of the front and rear images, resulting in the DFD visual illusion in Fig. 1. However, it needed a large volume for a given 3-D imaging area, so this method is unsuitable when the 3-D imaging area is small (e.g.,

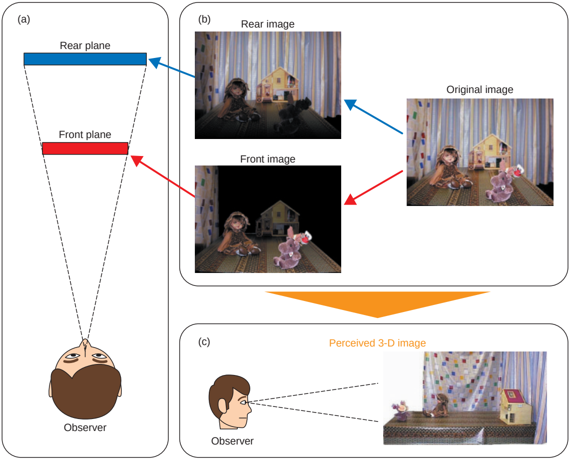

Fig. 1. Fundamental concept of DFD display using 3-D visual illusion.

in mobile devices).

3. Concept for a compact DFD display

Our latest idea for implementing a DFD display utilizes the summation of polarization rotation angles of two transparent LCDs instead of the luminance summation.

The conventional LCD display consists of an LCD cell, a polarizer, an analyzer, and a backlight (**Fig. 3**). The display luminance is determined by the change in polarization angle of the LCD cell. In the twisted nematic (TN) LCD, when the display is "black", the polarization angle is zero because the liquid crystal molecules turn vertically. For "white", the polarization angle is 90° because the liquid crystal molecules have twisted by 90°. In general, the polarization angle changes roughly between 0 and 90° to display "half tones". If the polarization angle is denoted by α, luminance can be expressed as $\sin^2\alpha$.

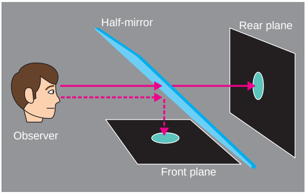

Fig. 2. Structure of DFD display using two non-transparent 2-D displays.

Our new concept for a compact DFD display is shown in **Fig. 4**. It consists of front and rear LCD cells, a polarizer, an analyzer, and a backlight. The front and rear LCD cells are placed between the polarizer and analyzer. As you can easily guess, when the polarization angle of the front or rear LCD cell is 0°, the luminance of only the front LCD cell increases when the polarization angle in the front LCD cell changes (because LCD cells on a usual LCD display are stacked) and that of only the rear LCD cell increases when the polarization angle in the rear LCD cell changes. When both the front and rear polarization angles are changed, the two polarization angles are roughly added. For simplicity, we can assume that the luminances are added, but actually it is not a simple addition.

There are three typical cases of polarization-angle changes as follows.

(1) When the polarization angles change by α° in

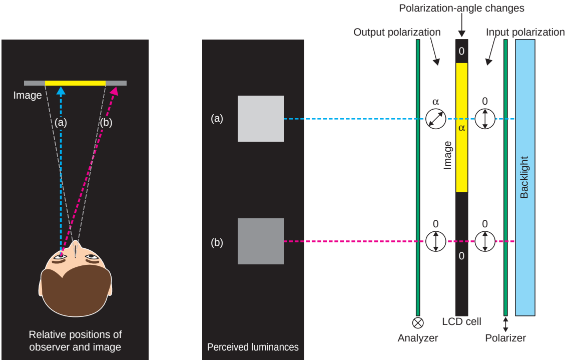

Fig. 3. Polarization-angle changes in conventional LCD.

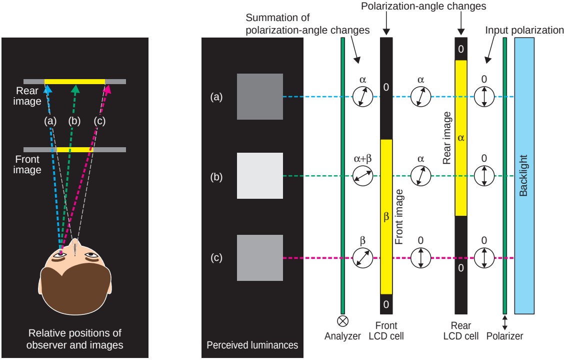

Fig. 4. Summation of polarization-angle changes in the compact DFD display.

the rear LCD and 0° in the front LCD, the sum of the polarization-angle changes is α°, as shown in Fig. 4(a). In this case, overall luminance $\sin^2\alpha$ has a value similar to the luminance of only the rear LCD cell.

(2) When the polarization angles change by 0° in the rear LCD and β° in the front LCD, the sum of the polarization-angle changes is β°, as shown in Fig. 4(c). In this case, overall luminance $\sin^2\beta$ has a value similar to the luminance of only the front LCD cell.

(3) When the polarization angles change by α° in the rear LCD and β° in the front LCD, the sum of the polarization-angle changes is α+β°, as shown in Fig. 4(b). In this case, the overall luminance is similar to $\sin^2(\alpha+\beta)$.

When a color 3-D image is displayed, the polarization angles at red, green, and blue filters are changed independently because both LCDs have color filters. This results in almost the same color images in the front and rear planes except for the luminance differences. This means that polarization-angle changes can be used instead of the direct luminance change in the DFD display shown in Fig. 1. Thus, we consider that the DFD visual illusion should also be perceived when we use polarization-angle changes.

In this paper, we show that stacking two TN type LCDs is an effective way to make the DFD display compact. We experimentally confirmed that the front and rear luminances are added as in the current DFD display with a half mirror.

4. Experiments and results

4.1 Experiments on summation of front and rear luminances

An experiment was performed to estimate the relationship between overall luminance and polarization-angle changes at the front and rear LCDs. The overall luminance was measured using the setup shown in Fig. 4 and a luminance measurement tool (CS-100, Minolta). Two TN type LCDs were used. The area where luminance was measured was set to 10 mmϕ around the LCD center by changing the image's gray scale. The front luminance was measured by setting the rear polarization angle to zero before the measurement, and *vice versa*. In the measurement, the luminance of the rear LCD cell was kept constant and the luminance of the front LCD cell was changed from minimum to maximum. Measurements were then repeated for several values of the rear luminance.

Figure 5 shows the relationship between overall luminance and front/rear luminances. Circles (rear luminance: 23%), squares (47%), and triangles (82%)

are experimental data. Broken lines are theoretical summations of front and rear luminances.

The results show that when the front and rear polarization-angle changes were added, the front and rear luminances were added approximately linearly. However, the deviations of measured luminances from the summation of front and rear luminances were up to 15% and the measured values were always larger. Specifically, when the luminance of the front or rear LCD cell was minimum ($\alpha+\beta=0°$) and the luminance sum was maximum ($\alpha+\beta=90°$), the deviation was almost zero. Except for these cases, there were some small deviations and the characteristics slightly curved.

The three conditions discussed in section 3 correspond to a linear addition of luminances. Other conditions correspond to non-linear addition. Therefore, we think that this assumption can explain the deviation from a theoretical summation of front and rear luminances, which appears to agree well with the experimental results.

Next, we investigated by a subjective test whether the luminance deviation caused by the summation of polarization-angle changes was the limiting factor of the DFD visual illusion in the DFD display.

4.2 Subjective test

Ten observers were asked to report where the depths of the stuffed animal, doll, and house were qualitatively perceived between the front and rear planes when they viewed the images shown in Fig. 1. The alignment and magnification of the two images were adjusted to overlap at the mid-viewpoint between the observer's eyes. The distance between the observer and the front plane was 500 mm, and the separation between the front and rear planes was 5.0 mm. This separation was chosen because the observer cannot easily perceive a double edge of the front and rear images [8].

The results were similar to those obtained for the current DFD, confirming that depth positions are similar. Moreover, the luminance was almost proportional to the depth position when a half mirror was used to overlap the front and rear planes [5]-[7]. Thus the maximum deviation in depth position is about 15% in this method. Therefore, we think that it is necessary to examine an image correction method. This subjective test confirmed the feasibility of expressing depth using the DFD display based on the summation of polarization-angle changes at the front and rear LCDs.

5. Prototype of the compact DFD display

We have developed a prototype of the compact DFD display, as shown in **Fig. 6**. The DFD display is simply composed of two transparent LCDs. These 4-inch LCDs have 640 pixels in the horizontal direction and 480 pixels in the vertical direction. The distance between the two LCDs is 5 mm. Thus, the 3-D imaging volume is 4 inches (102 mm) diagonally and 5 mm deep. This prototype shows that it is possible to make a DFD display that is more compact than the current one, which uses a half mirror. It also confirms the ability to display color moving 3-D images in a small depth area.

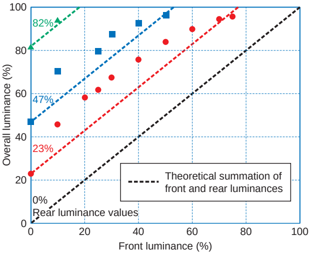

Fig. 5. Overall luminance change when the front and rear polarization angles changed.

3-D imaging volume: 4 inches diagonally and 5 mm deep

Fig. 6. Prototype of the compact DFD display.

6. Conclusion

A compact DFD display can be made using the summation of polarization-angle changes instead of direct luminance summation. A prototype using this method showed that color moving 3-D images can easily be produced between two conventional LCD cells. The simple structure without a half mirror or any moving parts should lead to high system reliability. Thus, our compact DFD display is promising for various applications, such as cellular phones, PDAs, and computer monitors.

In future studies, we intend to examine in detail the relationship between overall luminance and polarization-angle changes.

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